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A Study of Radon-222 Released from Water During Typical Household Activities

(U.S.) Eastern Environmental Radiation Facility, Montgomery, AL

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This report describes the results of a study to determine the fraction of radon released from water during typical household activities such as clothes washing, dishwashing, showering, etc., and estimates the potential radon concentration in air and resulting working levels in structures.

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Radiation

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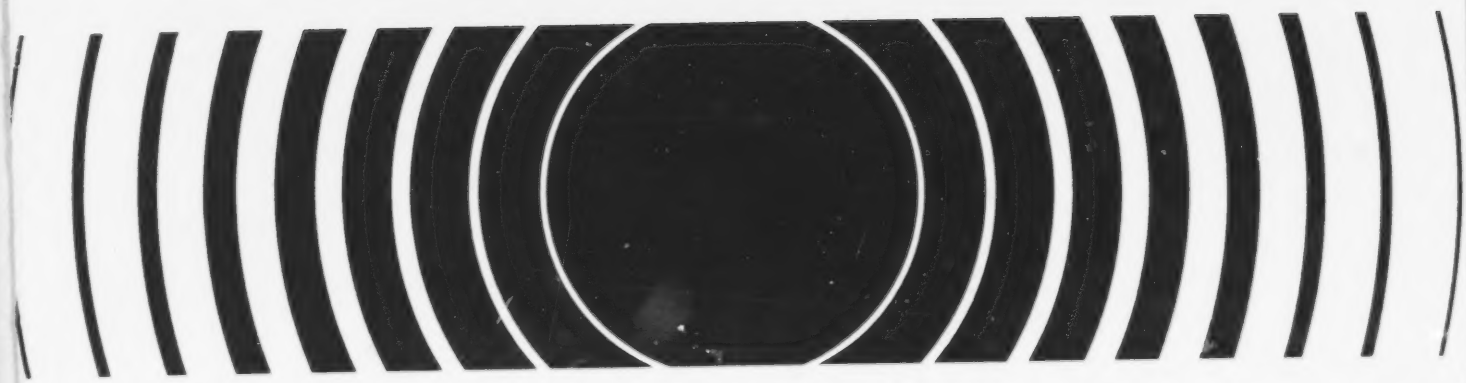

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Technical Note
ORP/EERF-79-1

A Study of Radon-222 Released from Water During Typical Household Activities

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I. Introduction

Radon-222 is an inert, noble gas formed by radioactive decay of radium-226. Radon-222 also undergoes radioactive decay by emission of alpha particles with a characteristic half-life of 3.82 days (1). Decay products of radon* include a series of short half-life radioactive isotopes including alpha, beta, and gamma emitters. All progeny are associated with particulates.

Small quantities of radon can be found in all ground water from natural sources as a result of decay of radium both in water and the rock and soil matrix surrounding the water. The concentration of radon in ground water may far exceed that of radium in the water because gaseous radon can migrate from the solid matrix into underground aquifers. Measurements of radon in water from selected water sources, including primarily thermal springs, were recorded as early as 1905 (2). These measurements showed a large variation in radon concentration between different thermal springs. Radon in water from many other areas has been measured since that time, and the results reported in various publications (3-6). A summary of the findings from these and several other studies was prepared by Duncan, et al., for the U.S. Environmental Protection Agency (EPA) (7). These reports indicate concentrations of radon in potable water supply systems ranging from 1,000 to 30,000 pCi/l. Specific geographic areas shown to have such high concentrations include Maine, North Carolina, Texas, Arkansas, Florida, and Utah.

Radon in drinking water has previously been considered a source of radiation exposure primarily from an ingestion standpoint. However, the EPA, Office of Radiation Programs (ORP), is investigating the potential for exposure to individuals from inhalation of gaseous radon released from water by various household and commercial processes. Dose estimates in the literature have also been based on radon progeny ingested with water. More recent data indicate that inhalation of radon and radon progeny may produce significantly higher exposures (7). To accurately predict the potential exposure from radon inhalation, it is necessary to have knowledge of the concentrations of radon in a water supply and what percentage of this radon is released by typical water uses, i.e., showers, dishwashers, clothes washers, etc. To obtain the latter information, the Eastern Environmental Radiation Facility (EERF) has investigated some typical residential water uses to determine the portion of radon released.

II. Objectives

The objectives of this study were to measure the fraction of radon released during typical household activities such as clothes washing, dishwashing, showering, etc., and to estimate the potential

* In this report, the term "radon" refers to radon-222.

radon concentrations in surrounding air and resulting working levels (WL)* in structures.

To accomplish these objectives, the EPA, EERF mobile lab was outfitted with a clothes washer and dishwasher, and a field trip was made to Polk County, Florida. Previous studies had shown elevated levels of radon in water which were associated with the phosphate deposits in the area.

III. Counting Technique and Calibration

The concentrations of radon in water were determined by using a liquid scintillation technique similar to the procedure described by Prichard and Gesell (8). The technique involves the introduction of 10 ml of water to be analyzed for radon into a liquid scintillation vial containing 10 ml of liquid scintillation counting solution. The mixture is then sealed and agitated and held for three hours to allow the short-lived radon daughters to reach equilibrium before counting. A single sample liquid scintillation counter was used in the mobile laboratory for sample analysis.

Calibration of the counting system was accomplished by preparing several liquid scintillation vials with 10 ml of the mix and 10 ml of radium-226 in water solution of known concentrations. These mixtures were then sealed and held for a minimum period of 30 days to allow the radon to reach equilibrium with the radium. Concentration of radium-226 used for calibration ranged from 0.8 pCi/ml to 3.6 pCi/ml. The calibration factor, using a broad spectrum counting procedure was determined to be 10.1 counts/min/pCi. The limit of detection for a 50-min. count and 10-ml sample was determined to be 0.16 pCi (9,10).

IV. Experimental Setup and Sampling Procedures

A. Supply Samples

To determine the radon removal fractions by the various household applications, it was first necessary to determine the concentration of radon in the incoming water supply. Supply samples were collected in accordance with the procedures outlined in Appendix A. By collecting the samples in this manner loss of radon to the air is minimized. Five supplies were sampled and analyzed during this study.

B. Clothes Washer and Dishwasher

Special plumbing was designed and constructed to allow the clothes washer and dishwasher installed in the EERF mobile laboratory to discharge in a normal manner into a glass p-trap

* Working level is defined as any combination of radon daughters in one liter of air that will result in the ultimate emission of 1.3×10^5 MeV of potential alpha energy.

which was used as a sampling point. Samples were collected from the p-trap by inserting a hypodermic needle through a rubber septum in the bottom of the trap. The samples were injected into the sample vials as described earlier and analyzed using the liquid scintillation counter. Samples were collected from the trap following each of the various clothes and dishwasher wash and rinse cycles. Other variables such as water temperature, amount of detergent added, and length of wash or rinse cycles were examined. Identical studies were performed at several locations with varying concentrations of radon in the supply water.

C. Tub, Shower, Toilet, and Sink

To determine the radon released by a tub, shower, toilet, and sink, three homes were selected which had water supplies with elevated radon in water concentrations.

Radon released by the shower was determined by (1) operating the shower for several minutes with the drain open, (2) closing the drain, (3) turning off the shower, and (4) collecting a sample from the bottom of the shower using a hypodermic needle as described earlier. The concentration in this sample was compared to the concentration in the supply water before exposure to the atmosphere to determine the percent removed.

A similar experiment was performed with a tub. The tub was filled with water to a normal bathing level, and the water was agitated to simulate bathing. All of the water was drained from the tub except a small portion from which a sample was collected with a hypodermic needle. The concentration in this sample was compared with the supply concentration.

Samples were collected from the toilet bowl and tank before and after flushing and refilling to determine the amount of radon released to the air by this operation.

Radon released by running water into a sink was also determined. The sink was partially filled and the water agitated. The majority of the water was drained and a sample was collected from the remaining water with a hypodermic needle.

V. Results

A. Supply Concentrations

Radon-222 concentrations in the various water supplies sampled during this study are shown in table 1. These five supplies were all private wells that served from 1 to 10 families. No information was available concerning the depth of the wells.

Table 1

Radon-222 in Water Supplies

Water Supply	^{222}Rn Concentration pCi/l + 2 σ
1 Trailer park and residence	4,148 ± 203 (1)
2 Campground	2,955 ± 260 (1)
3 Service station	5,014 ± 117 (2)
4 Welding shop	5,356 ± 327 (2)
5 Private residence	8,649 ± 442 (2)

(1) Mean of 10 samples.

(2) Mean of 4 samples.

B. Radon-222 Removal Experiment

1. Clothes Washer

The clothes washer used in these experiments had two cycles, regular and gentle. The regular cycle had a maximum agitation period of 18 minutes followed by a short rinse cycle. The gentle cycle was similar to the regular cycle except the degree of agitation was less. The lengths of agitation and the water temperatures were variable on both wash cycles. The lengths of the rinse cycles were preset in both cases and the rinse cycles used cold water.

Radon released by clothes washing as a function of several parameters is shown in table 2. The length and degree of agitation appear to have a significant effect on radon removal as evidenced by the difference in the regular and gentle cycle results and the difference in the 18-, 11-, and 4-minute agitation periods. There also appears to be a difference in removal as a function of water temperature. The addition of soap to the water did not appear to have any significant effect.

2. Dishwasher

The dishwasher used in these studies had two wash cycles and four rinse cycles. Samples were collected following both wash and rinse cycles. The results, as shown in table 3, showed no significant difference in radon release between the wash and the rinse cycles.

3. Tub, Shower, and Sink

The three homes visited during this study had two showers and only one tub/shower combination. The results of these experiments are shown in table 3. Water temperature again appeared to have significant effect on the radon released in the tub use. Only one sink experiment was performed during this study with the results given in table 3.

4. Toilet

These experiments were performed by flushing the toilet and allowing the tank to refill with fresh supply water. A sample was collected from the tank and the toilet was flushed a second time. After the tank and bowl had refilled, a sample was collected from the bowl. These radon release results for the two stages of flushing are shown in table 3.

Table 2

^{222}Rn Released by Clothes Washer

Wash Parameter	% Rn Released ± 2 σ
Hot wash cycle (18 min.) with soap	98.4 ± 1.3
Hot wash cycle (18 min.) without soap	97.9 ± 2.7
Cold wash cycle (18 min.) with soap	93.3 ± 5.2
Cold wash cycle (18 min.) without soap	93.5 ± 3.4
Warm wash cycle (18 min.) with soap	98.3
Cold wash cycle (11 min.) with soap	91.4
Cold wash cycle (4 min.) with soap	84.7
Cold wash gentle-cycle with soap	78.7
Cold wash gentle-cycle without soap	76.6
Cold rinse regular cycle	80.9 ± 17.4
Cold rinse gentle cycle	62.2

Table 3

^{222}Rn Released by Other Household Applications

Applications	% Rn Released ± 2 σ
Dishwasher	
Wash cycle	97.7 ± 3.7
Rinse cycle	98.5 ± 2.1
Tub	
Hot water	59.7
Warm water	36.2
Cold water	37.8
Shower (warm)	71.2 ± 4.7
Sink (warm)	28.3
Commode	
Tank	4.9 ± 11.3
Bowl	23.6 ± 6.5

VI. Modeling Radon in a Closed Structure

Since the quantity of radon-222 in potable water supplies ranges over several orders of magnitude, a generalized model will be presented with several examples of how certain variables affect the amount of radon in a closed structure and the resulting daughter distribution. No attempt has been made to show the influence of running a central air conditioning system, window air conditioner or fan, or any other air moving device on the indoor radon concentration except by varying the ventilation rate, i.e., air changes/hr. Furthermore, radon daughter plate out and filtration are not included in this assessment which makes the working level estimates conservative since working level values are dependent on daughter concentrations.

A FORTRAN program (Appendix B) entitled WLSIMO (working level simulation output) was developed to run on the EERF PDP-11 minicomputer. This program numerically solves a series of first order linear differential equations known as the Batement equations. The output format includes radon concentration (pCi/l) and working level at time (t), and the average radon concentration (pCi/l) and working level for the total period of interest. A sample input for WLSIMO can be found in Appendix B.

To estimate the buildup of radon and its progeny in a home from potable water supplies, the typical water usage rates in a household situation must be known. These rates are given in table 4 in units of gallons per day per person (gpdpp) with an average individual usage rate of 20 to 80 gpdpp (11). This information was combined with the radon release data for each household water use (tables 2 & 3) and typical radon in water concentrations to determine the potential radon release for a typical residence.

As mentioned before, several examples will be given to show a general range of what might be expected in the buildup of radon and its daughters. Table 5 describes a plausible situation involving a family of four in which typical household uses of water are included.

The radon source term is expressed in units of pCi/l-min. This particular unit is needed in modeling the radon buildup in a closed structure. In physical terms, it can be thought of as an incremental radon concentration increase in air per minute. For example, a source term of 0.06 pCi/l-min represents an increase in radon concentration in air of 0.06 pCi/l every minute.

Figure 1 demonstrates the daily cyclic nature of the radon concentration and working level resulting from a radon in water concentration of 10,000 pCi/l. The radon concentration and working level values are instantaneous values for a given time of day. It was assumed that both values were zero at and before 7:00 a.m. The maximum radon concentration occurred at 9:00 p.m. with a corresponding maximum working level value at about 10:00 p.m. The average radon concentration and working

Table 4

Individual Water Usage Rates

Radon Source	Water Usage Rate (gal/day/person (11)
Washing machine	20-30
Washing dishes	8-10
Bath	30-40
Shower	20-30
Toilet	4- 6

Table 5

Daily Composite Radon Source Term

	Source	Quantity (gal.)	%Rn	Source Term (pCi/l-min)*
Start- 0700 (7:00 am)	Shower	25	.71	-
Stop - 0730 (7:30 am)	Toilet	12 (4 people X 3 gal.)	.28	-
	Total	-	-	0.06
Start- 0900 (9:00 am)	Washing	25	.95	0.033
Stop- 1000 (10:00 am)	Machine			
Start- 2000 (8:00 pm)	Bath	35	.50	-
Stop- 2100 (9:00 pm)	Toilet	12 (4 people X 3 gal.)	.28	-
	Washing dishes	9	.98	-
	Bath or shower (2 children)	30	.60	-
	Total	-	-	0.066
	Grand Total	148 gal. (560 l)	-	-

*[radon] water = 10,000 pCi/l; house volume = 4.53×10^5 l (corresponds to a 2,000 ft^2 house)

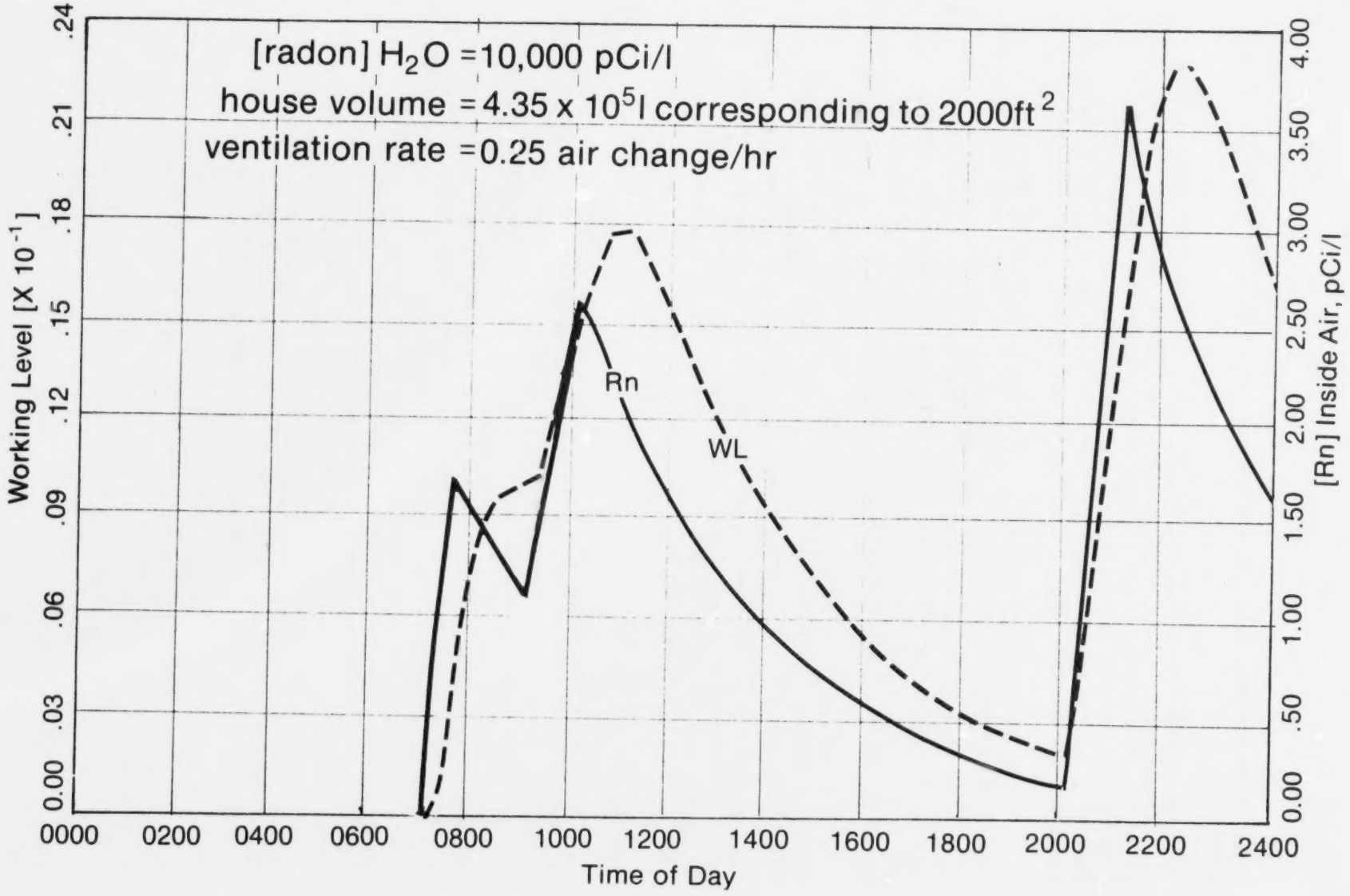

Figure 1. Daily radon concentration and working level with time.

level value for the 24-hr. period are 0.97 pCi/l and 0.0074, respectively.

The effects of varying ventilation rates with constant house volume and varying house volumes with constant ventilation rates are shown in figure 2. The average radon concentration and working level decreases with increasing ventilation rate if the house volume is held constant. Similarly, as the house volume increases, holding the ventilation rate constant, the average radon concentration and working level decreases.

Figure 3 graphically exhibits the change in average WL and radon concentration with varying average radon water concentrations with a constant ventilation rate of one air change per hour and a constant volume of 3.4×10^5 l corresponding to a 1500 ft^2 house. As the average radon in water concentration increases, the average radon concentration in air and WL increase proportionately. Figures 2 and 3 are based on the water usage presented in table 5.

A recent paper by Gesell and Prichard (1978) (12) models radon in a home situation. Results similar to the ones presented in this paper are given. An even more recent modeling effort was undertaken by O'Connell and Gilgan (1978) (13) for radon bearing geothermal waters. Even though three different modeling approaches were used, the average radon concentrations predicted by each model (Gesell and Prichard, (12) O'Connell and Gilgan, (13) and this paper) are nearly the same if the same parametric values are used as input.

VII. Summary and Conclusions

No attempt has been made to transform the radon concentrations in air and/or working level to dose and/or health effects. The primary objective of this study was to determine radon release fractions for typical water uses for use in modeling efforts to estimate the potential exposure levels in a typical residence. The techniques used for measurement of radon released from water seemed somewhat crude in some cases; however, the results agree well with other similar experiences and common sense expectations. In general, the results indicate that agitation and heating both increase the release of gaseous radon from water. There was some surprise that even a small amount of agitation, i.e., running water into a sink or through a shower, did not cause complete release of all radon. Additional measurements of this type will be performed as a part of a continuing study of radon exposure from natural sources. The EERF, in cooperation with many state and local health departments, is presently conducting a survey of radon concentrations in selected public water supplies throughout the country.

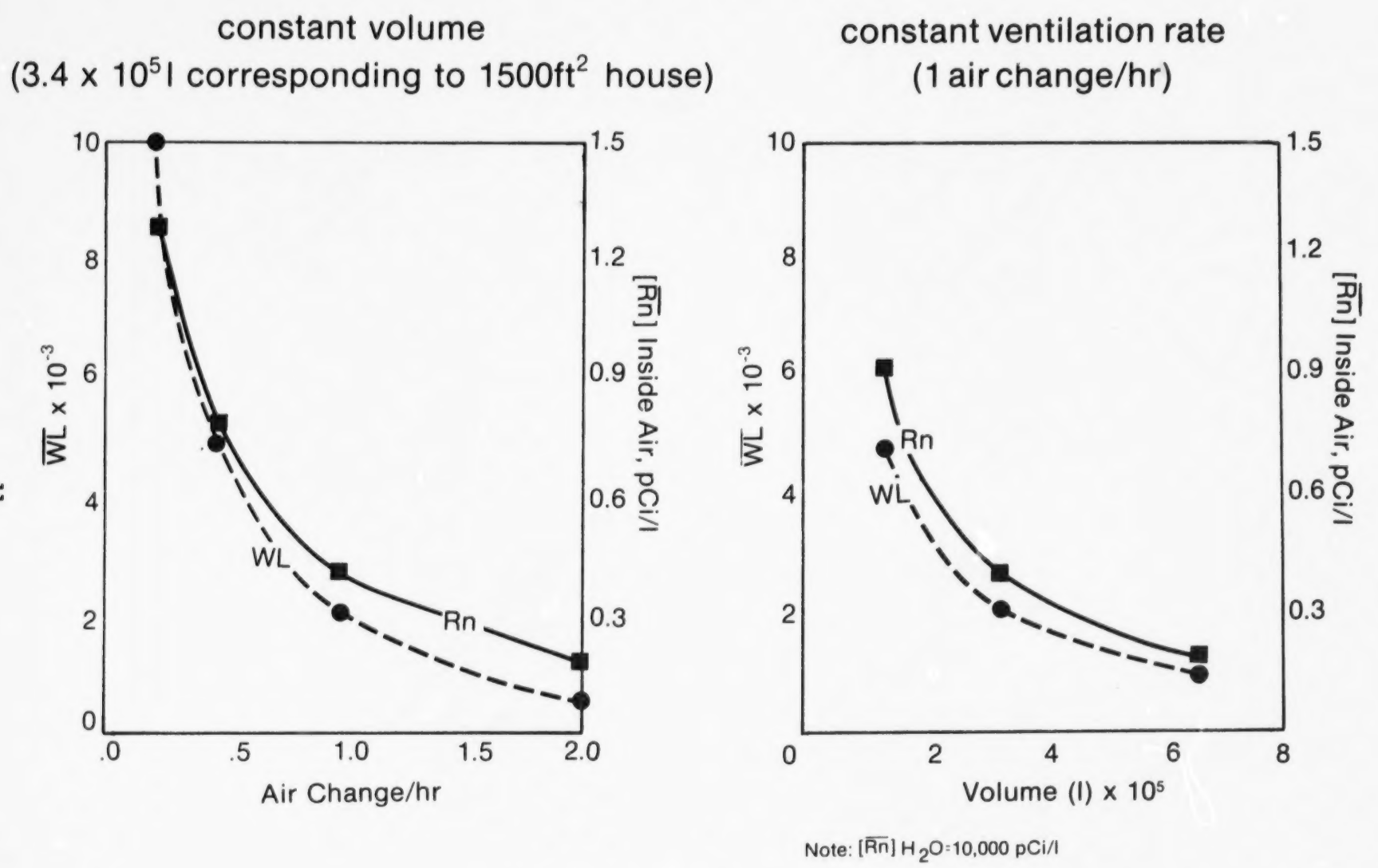

Figure 2. Sensitivity Analyses.

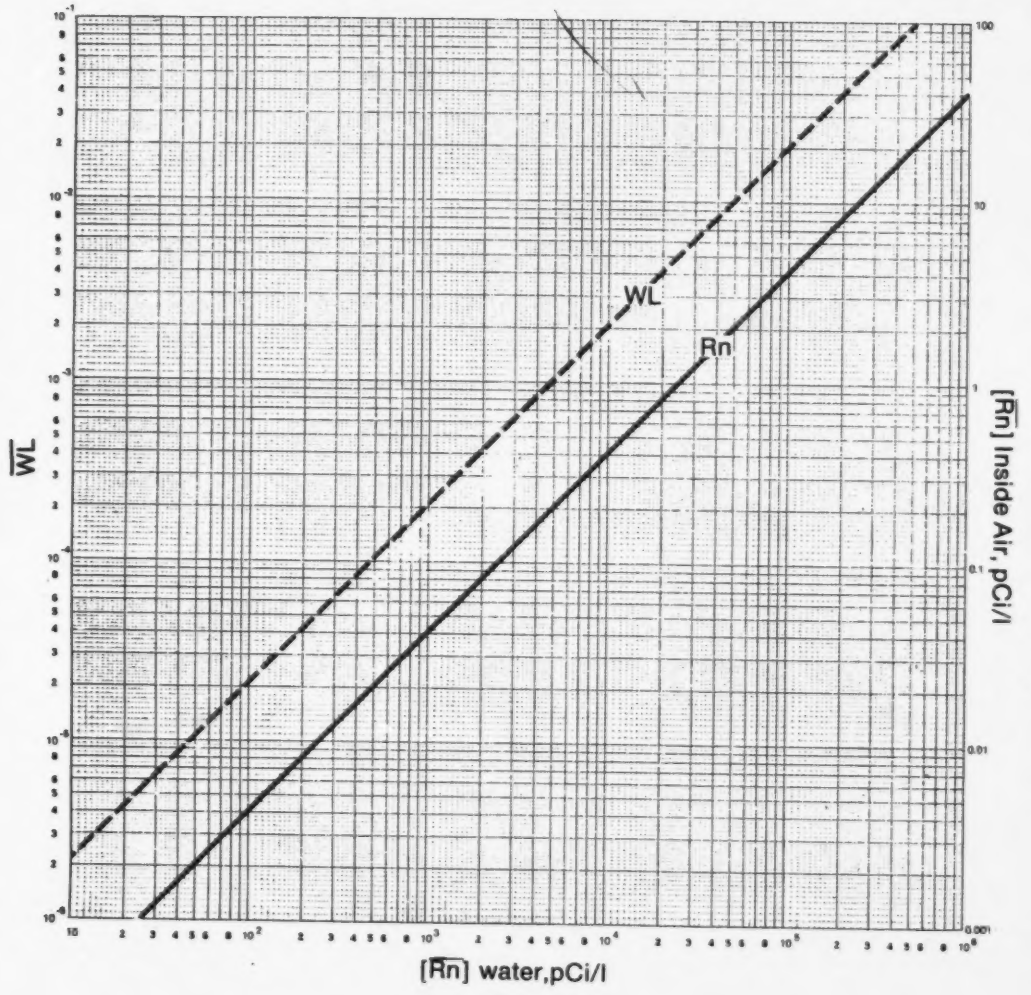

Figure 3. Average radon and working level variations with different average radon water concentrations.

REFERENCES

1. Radiological Health Handbook, PHS Publication No. 2016, p. 363, January 1970.

2. BOLTWOOD, B. B. On the radioactive properties of the water of the springs on the Hot Springs Reservation, Hot Springs, Arkansas; Amer. Jour. Sci. 4th Ser., V. 20, p. 128-132 (1905).

3. KURODA, P. K., P. E. DAMON, and H. I. HYDE. Radioactivity of the Spring Waters of Hot Springs National Park and Vicinity in Arkansas. Amer. Jour. Sci., Vol. 252, February 1954, pp. 76-86.

4. SMITH, B. M., W. N. GRUNE, F. B. HIGGINS, JR., and J. G. TERRILL, JR. Natural Radioactivity in Ground Water Supplies in Maine and New Hampshire. Jour. American Water Works Asso., Vol. 53, No. 1, January 1961, pp. 75-88.

5. ALDRICH, LESTER KYLE, III, M. K. SASSER, and D. A. CONNERS, IV. Evaluations of Radon Concentrations in North Carolina Ground Water Supplies, Dept. of Human Resources, Division of Facility Services, Radiation Protection Branch, Raleigh, North Carolina, January 1975.

6. O'CONNELL, M. F. and R. F. KAUFMANN. Radioactivity Associated with Geothermal Waters in the Western United States, U.S. Environmental Protection Agency Technical Note, ORP/LV-75-8A, March 1976.

7. DUNCAN, D. L., T. F. GESELL, and R. H. JOHNSON, JR. Radon-222 in Potable Water, Proceedings of the Health Physics Society 10th Midyear Topical Symposium:Natural Radioactivity in Man's Environment, October 1976.

8. PRICHARD, H. M. and T. F. GESELL, Rapid Measurements of ^{222}Rn Concentrations in Water with a Commercial Liquid Scintillation Counter, Health Physics, Vol. 33, No. 6, pp. 577-581, December 1977.

9. ALTSHULER, B. and B. PASTERNACK. Statistical Measures of the Lower Limit of Detection of a Radiation Counter, Health Physics 9, 293, 1963.

10. CURRIE, LOYD A. Limits for Qualitative Detection and Quantitative Determination - Application to Radiochemistry, Analytical Chemistry, Col. 40, No. 3, March 1968, pp. 586-593.

11. Water Use in the United States. U.S. Department of Interior.

12. GESELL, T. F. and H. M. PRICHARD. The Contribution of Radon in Tap Water to Indoor Radon Concentration. Book of Summaries The Natural Radiation Environment III. Houston, TX, April 1978.

13. O'CONNELL, M. F. and G. A. GILGAN. Radioactivity Associated with Geothermal Waters in the Western United States. A Modeling Effort to Calculate Working Levels of Radon-222 and its Progeny for Nonelectrical Applications. USEPA Technical Note. ORP/LV-75-8B, 1978.

Appendix A

Radon in Water Sampling Procedures

A. Sampling kits (figures 1-A and 2-A) are small lightweight carrying cases complete with all materials necessary for collecting potable water samples for radon-222 analysis.

Each kit contains the following equipment:

1 - sampling funnel and tube with standard faucet fitting

1 - slip-on faucet adapter

2 - 20-ml syringes

2 - 18-gauge, 2-inch hypodermic needles

20 to 30 - glass scintillation vials with 10-ml solution, each

B. Sample Collection

1. Attach the sampling funnel and tube to a faucet with either the standard faucet fitting or adapter (figure 3-A).

2. Slowly turn on the water and allow a steady stream to flow out of the funnel for approximately 2 minutes. This purges the tube and assures a fresh sample.

3. Reduce the flow of water and invert the funnel (figure 4-A). The flow should be adjusted to a level that does not cause turbulence in the pool of water contained in the funnel. Allow excess water to spill over one edge of the funnel.

4. Examine the hose connection and tubing for air bubbles or pockets. If these are visible, raise or lower the funnel until they are removed.

5. Place the tip of the hypodermic needle approximately 3 cm under the surface of the water in the funnel and withdraw a few ml of water and eject this water. Using this procedure, rinse the syringe and hypodermic needle two or three times.

6. Again, place the tip of the needle approximately 3 cm below the surface of the water and withdraw 12 to 15 ml (figure 5-A). NOTE: The water should be pulled into the syringe slowly to avoid extreme turbulence and collection of air bubbles. If large air bubbles are noticed in the syringe, the sample should be ejected and redrawn.

7. Invert the syringe and slowly eject any small air bubbles and extra water (figure 6-A). Retain precisely 10 ml of water in the syringe.

8. Remove the cap from a vial and carefully place the tip of the needle into the bottom of the liquid scintillation solution (figure 7-A). Slowly eject the water from the syringe into the vial. NOTE: The water is injected under the liquid scintillation solution to prevent loss of radon from the sample. If the water is forced out of the syringe with much pressure, it will cause turbulence in the solution and could result in loss of radon.

9. Carefully withdraw the hypodermic needle from the vial and replace the cap. The cap should be tightly secured to prevent leakage.

10. Repeat the previous steps to obtain two separate samples from each source. This completes the sample collection.

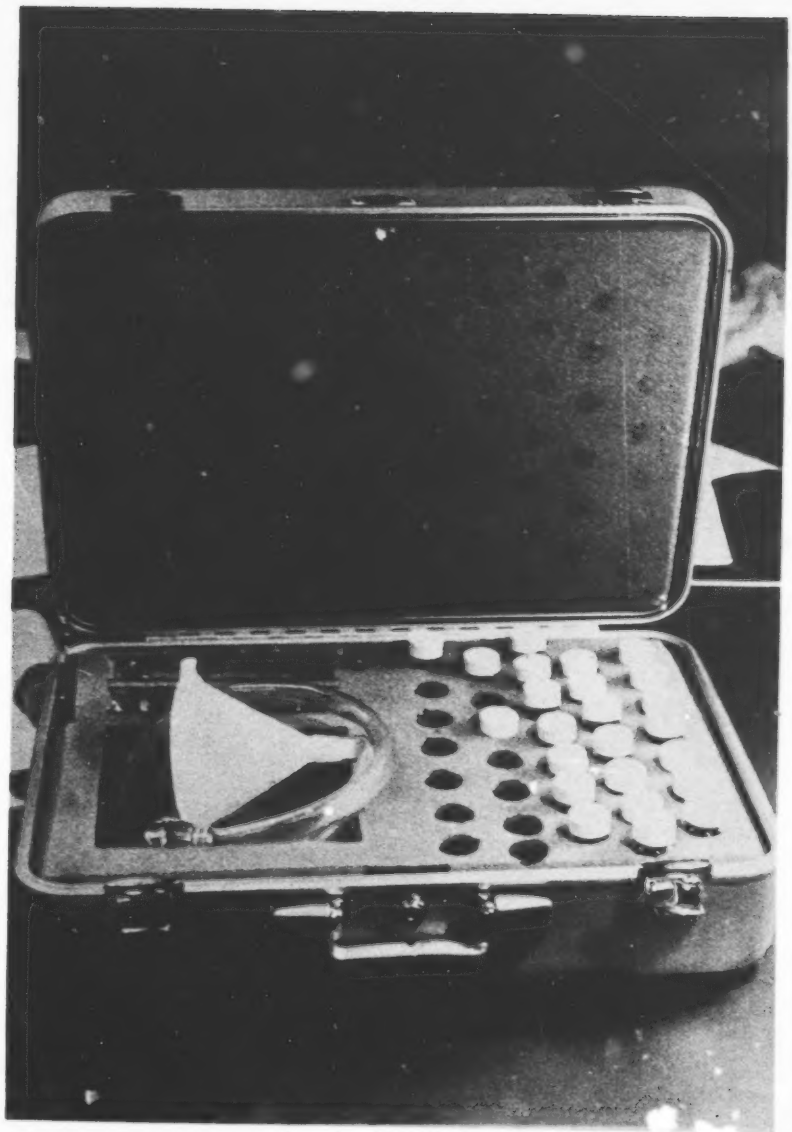

Figure 1A. Radon in water - sampling kit.

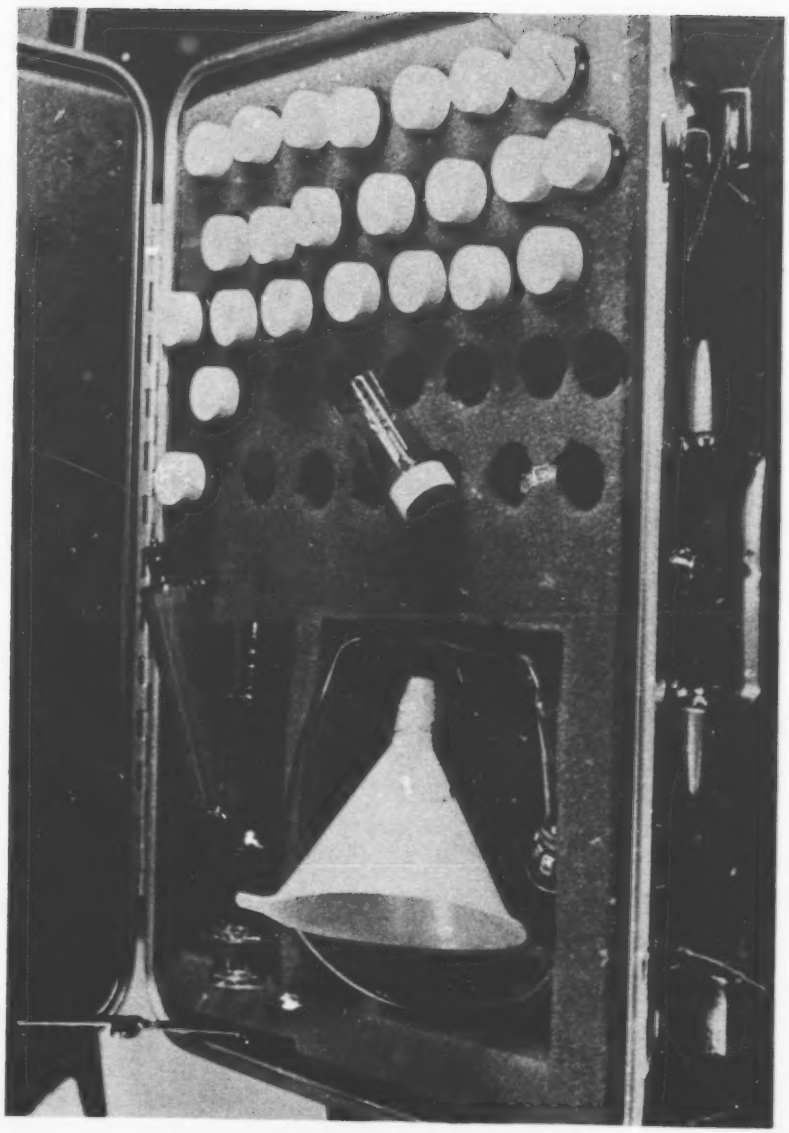

Figure 2A. Radon sampling kit - close-up.

Figure 3A. Connect tube to water supply.

Figure 4A. Allow water to slowly collect in funnel.

Figure 5A. Withdrawing water sample with syringe.

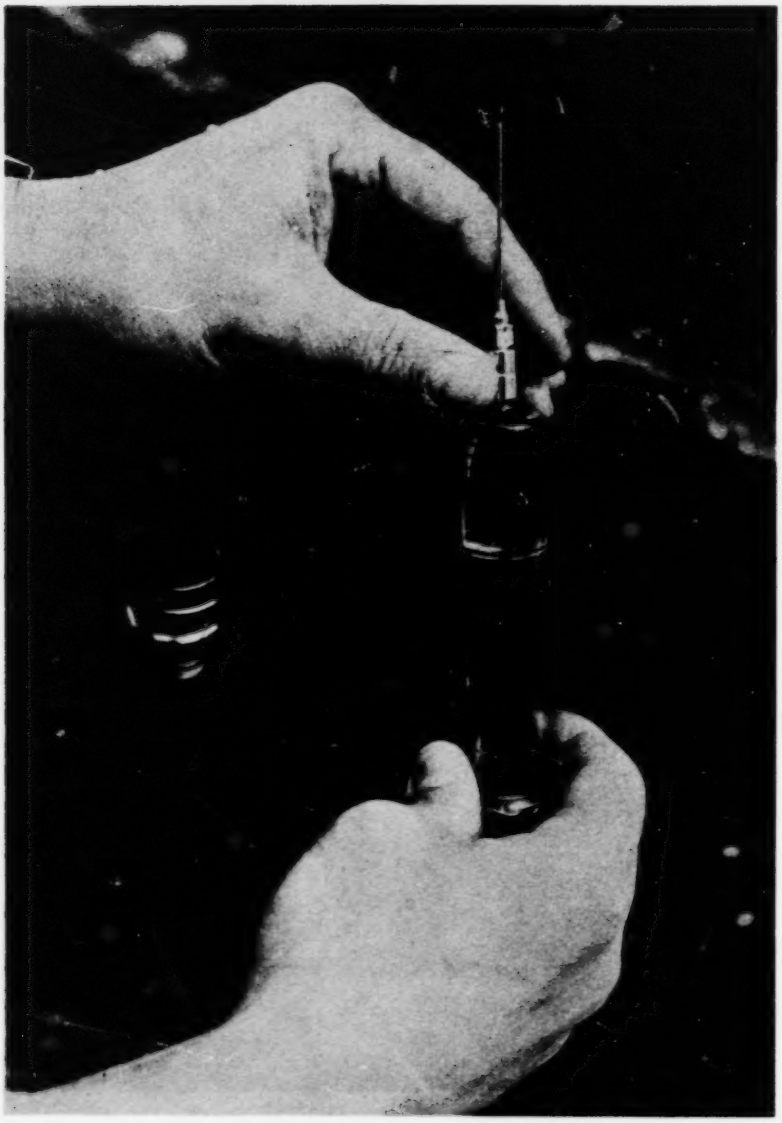

Figure 6A. Eject air bubbles and excess water.

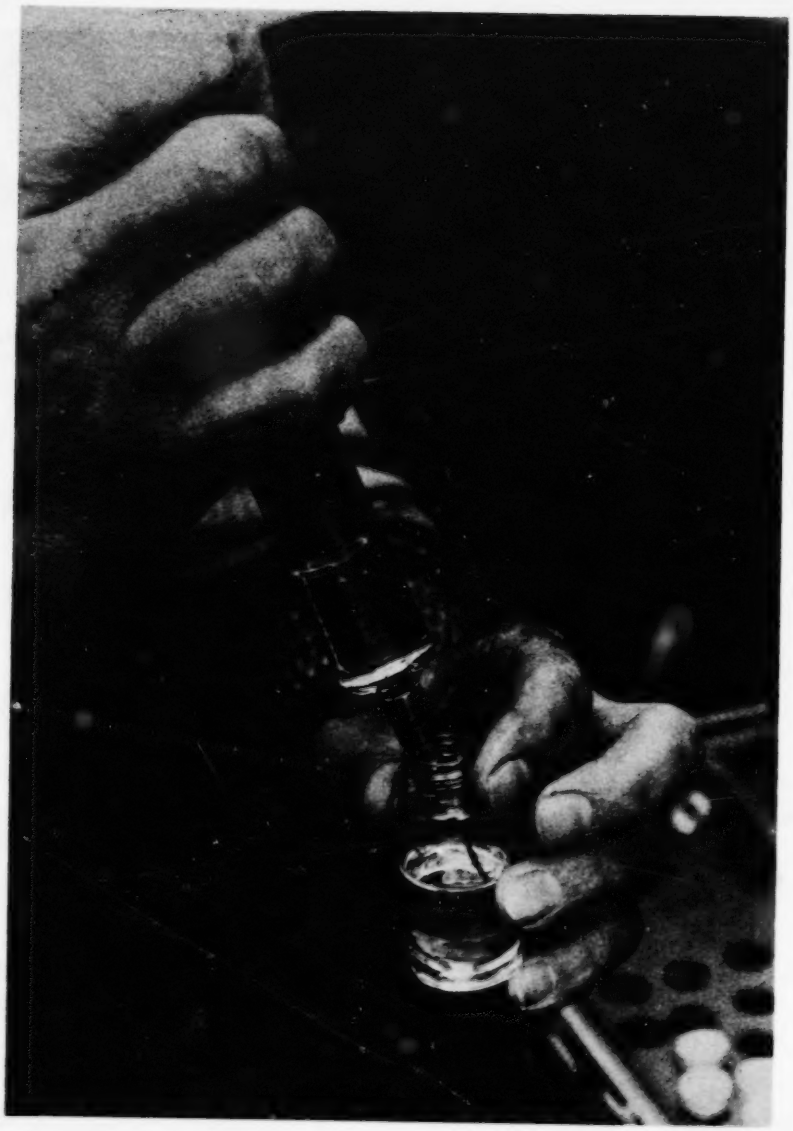

Figure 7A. Inject sample into sample vial.

Appendix B

FORTRAN Program

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C----     WLSIMO.FTN
C----           A PROGRAM TO SIMULATE THE BUILDUP OF RADON AND ITS
C----           DAUGHTERS IN A CLOSED STRUCTURE.  THE RUNGE-KUTTA
C----           METHOD IS USED IN SOLVING A SERIES OF DIFFERENTIAL
C----           EQUATIONS. (BATEMAN EQNS)
C----
      DIMENSION A(4),XLD(4),YL(4),DEL1(4),DEL2(4),DEL3(4),DEL4(4)
      DOUBLE PRECISION T,H
      LOGICAL *1 FNAME(30)
      LOGICAL *1 GNAME(30)
      DATA XLD/1.259E-4,.227,.0259,.0352/
      F(T,ARN)=P-(XL1+XL2+XLD(1))*ARN
      G(T,B,C,N)=XLD(N-1)*B-YL(N)*C
   14 WRITE(5,15)
   15 FORMAT(' INPUT FILE? 'S)
      READ(5,20,ERR=1000)LTH,FNAME
   20 FORMAT(Q,30A1)
      FNAME(LTH+1)=0
      OPEN(UNIT=3,NAME=FNAME,READONLY,TYPE='OLD')
      WRITE (5,200)
200   FORMAT(' OUTPUT FILE? 'S)
      READ(5,210,ERR=1000)LTH,GNAME
210   FORMAT(Q,30A1)
      GNAME(LTH+1)=0
      OPEN(UNIT=1,NAME=GNAME,TYPE='NEW')
      RSUM=0.0
      T=0.0
      ASUM=0.0
      JJ=1
C     H=TIME INTERVAL BETWEEN CALCULATIONS(NORMALLY 1.0 MIN);TLAST=
C     TOTAL TIME(MIN);XL1=LEAKAGE RATE(1/MIN);P=SOURCE TERM(PCI/L MIN)
C     ;A(1)=INITIAL RN-222 ACTIVITY(PCI/L);WL=INITIAL WORKING LEVEL;
C     A(2)=INITIAL RAA ACTIVITY(PCI/L);A(3)=INITIAL PAB ACTIVITY(PCI/L)
C     ;A(4)=INITIAL PAC ACTIVITY(PCI/L);M=0;MM=1 IF NEW P IS DESIRED.
C     LL=1 IF ONLY ONE P IS DESIRED (I.E. CONSTANT P).
C
      READ(3,25)H,TLAST,XL1,P,A(1),WL
      READ(3,25)A(2),A(3),A(4)
      READ(3,100)M,MM,LL
100   FORMAT(3I5)
   25 FORMAT(6F10.0)
      DO 27 N=1,4
27     A(N)=(A(N)/XLD(N))*2.22
      P=(P/XLD(1))*2.22
C     TI=INTERMEDIATE TIME(MIN-1 MIN);XL2=VENTILATION RATE(1/MIN);
C     XLPA=PLATEOUT RAA(1/MIN);XLPB=PLATEOUT RAB(1/MIN);XLPC=
C     PLATEOUT RAC(1/MIN)
C
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```
   30     READ(3,25)1T,XL2,XLPA,XLPB,XLPC
C         READ NEW P(PCI/L MIN)
          IF(LL.EQ.1) GO TO 35
          IF(MM.GT.1) READ(3,25) P
          IF(MM.GT.1) P=(P/XLD(1))*2.22
          MM=MM+1
   35     CONTINUE
          N=1
          ARN=A(1)
          DEL1(1)=H*F(T,ARN)
          DEL1C=DEL1(1)
          DEL2(1)=H*F(T+H/2.,ARN+DEL1C/2.)
          DEL2C=DEL2(1)
          DEL3(1)=H*F(T+H/2.,ARN+DEL2C/2.)
          DEL3C=DEL3(1)
          DEL4(1)=H*F(T+H,ARN+DEL3C)
   36     N=N+1
          IF(N.EQ.5)GO TO 45
          YL(2)=XL1+XL2+XLD(2)+XLPA
          YL(3)=XL1+XL2+XLD(3)+XLPB
          YL(4)=XL1+XL2+XLD(4)+XLPC
          B=A(N-1)
          C=A(N)
          DEL1(N)=H*G(T,B,C,N)
          DEL1R=DEL1(N)
          DEL2(N)=H*G(T+H/2.,B,C+DEL1R/2.,N)
          DEL2R=DEL2(N)
          DEL3(N)=H*G(T+H/2.,B,C+DEL2R/2.,N)
          DEL3R=DEL3(N)
          DEL4(N)=H*G(T+H,B,C+DEL3R,N)
          GO TO 36
45        IF(M.EQ.1) GOTO 110
          A(1)=A(1)*XLD(1)/2.22
          IF(JJ.EQ.1) GO TO 46
          GO TO 56
300       A(2)=A(2)*XLD(2)/2.22
          A(3)=A(3)*XLD(3)/2.22
          A(4)=A(4)*XLD(4)/2.22
          GO TO 47
46        WRITE(1,50)T,WL,A(1)
47        IF(T.GT.TLAST) WRITE(1,55) A(2),A(3),A(4)
55        FORMAT(1X,3E12.4)
56        A(1)=(A(1)/XLD(1))*2.22
          IF(T.GT.TLAST) GO TO 310
          GO TO 110
310       A(2)=(A(2)/XLD(2))*2.22
          A(3)=(A(3)/XLD(3))*2.22
          A(4)=(A(4)/XLD(4))*2.22
          GO TO 70
   50     FORMAT(1X,F10.3,3X,E12.4,3X,E12.4)
110       ASUM=ASUM+A(1)
```

```
      RSUM=RSUM+WL
      JJ=JJ+1
      IF(JJ.EQ.11) JJ=1
      DO 60 N=1,4
60    A(N)=A(N)+(DEL1(N)+2.*DEL2(N)+2.*DEL3(N)+DEL4(N))/6.
      WL=(A(2)*13.68+A(3)*7.68+A(4)*7.68)/(1.3E5)
      T=T+H
      IF(T.GT.TLAST) GOTO 300
      IF(T.GT.TT) GOTO 30
      GOTO 35
 70   AVE=ASUM/(TLAST/H+1.)
      WLAV=RSUM/(TLAST/H+1.)
      AVE=AVE*XLD(1)/2.22
      WRITE(1,99) AVE,WLAV
99    FORMAT(1X,2F12.4)
      CLOSE(UNIT=3)
      CLOSE(UNIT=1)
      WRITE(5,80)
 80   FORMAT(' MORE FILES(Y=YES,N=NO) '$)
      READ(5,85)IMORE
 85   FORMAT(A2)
      IF(IMORE.EQ.'Y ') GOTO 14
      STOP
1000  WRITE(5,1005)
1005  FORMAT(' ERROR--RE-ENTER FILE NAME. ')
      GOTO 14
      END
```

Sample Input

```
1.0         1440.       .0168       0.0         0.0         0.0
0.0         0.0         0.0
    0     1
419.0       0.0         0.0         0.0         0.0
449.0       0.0         0.0         0.0         0.0
0.06
539.0       0.0         0.0         0.0         0.0
0.0
599.0       0.0         0.0         0.0         0.0
0.033
1199.0      0.0         0.0         0.0         0.0
0.0
1259.0      0.0         0.0         0.0         0.0
0.066
1440.0      0.0         0.0         0.0         0.0
0.0
```


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